Harnessing The Micro Revolution:

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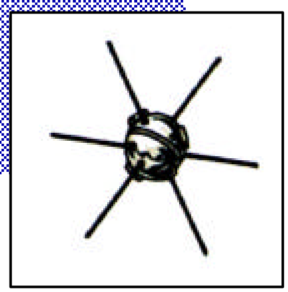
August 11, 1999

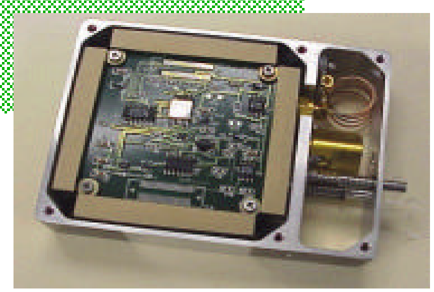
THE AEROSPACE CORPORATION

A “Micro” Revolution for Spacecraft

The Evolution of Manufacturing:

Custom assembly of non-standard parts → **Custom assembly of standardized parts** → **Assembly-line manufacturing (serial)** → **Batch-processing (parallel)**





Small Spacecraft:	Vanguard 1	DARPA PICOSAT	“Integrated” Satellites
Launch Year:	1958	1999	~2005
Functional Elements:	~100	~100,000	~100,000,000

Microelectronics: The Evolution of a Revolution

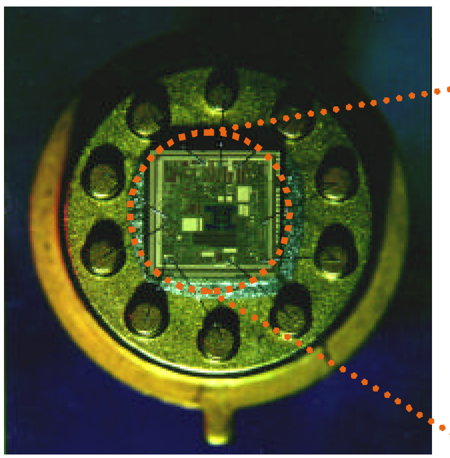
Year:	Smallest Feature (microns)	Dynamic RAM: Die Size (cm^2)	Dynamic RAM: Billions of Bits per Dice	Microprocessors: Die Size (cm^2)	Microprocessors: Millions of Transistors per cm^2
1995	0.35	1.9	0.064	2.5	4
1998	0.25	2.8	0.256	3.0	7
2001	0.18	4.2	1	3.6	13
2004	0.13	6.4	4	4.3	25
2007	0.10	9.6	16	5.2	50
2010	0.07	14	64	6.2	90

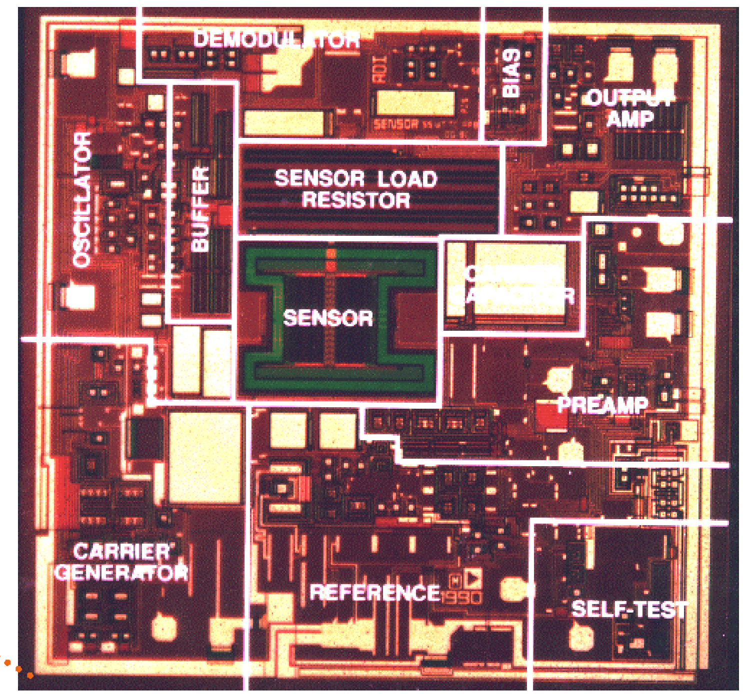
The microelectronics "revolution" continues along a predictable path

From "Technology 1996: Solid State", *IEEE Spectrum*, **33** #1, p. 51-55, January 1996

A REVOLUTION IN MECHANICAL CONSTRUCTION: MICROELECTROMECHANICAL SYSTEMS (MEMS)

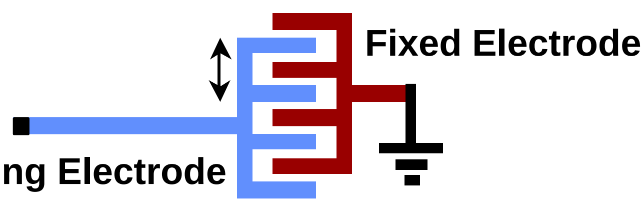
Analog Devices ADXL50 Accelerometer





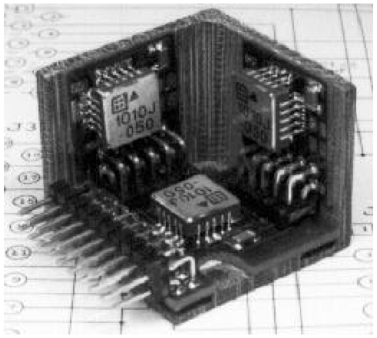
3 millimeters

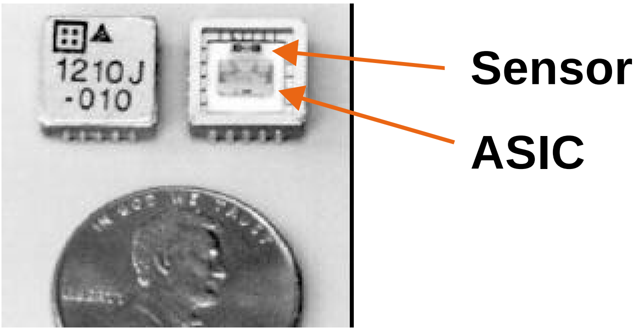
Principle of operation:

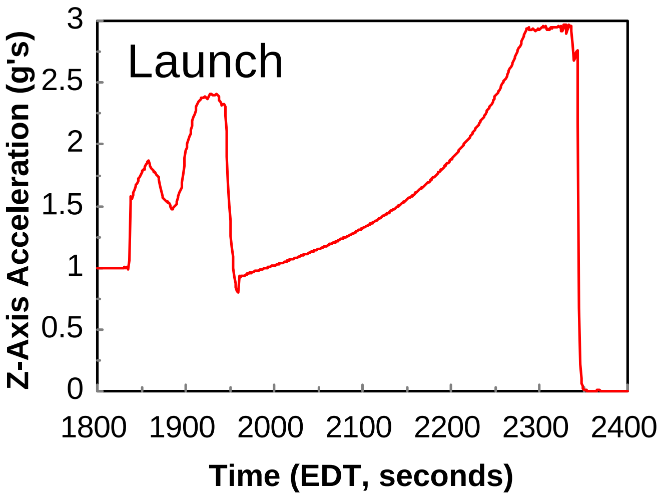


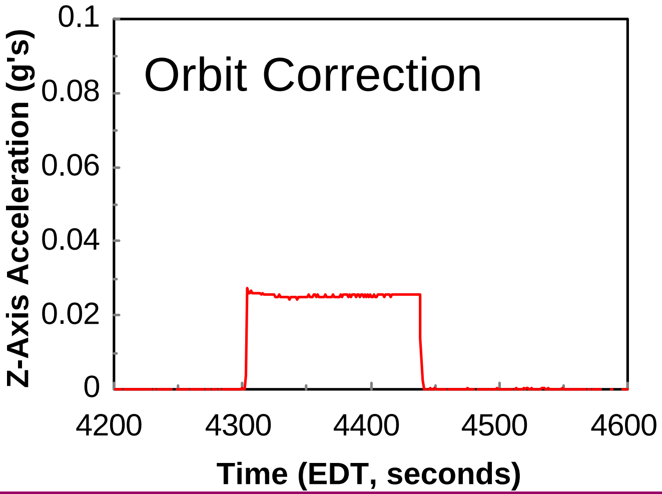
MEMS Accelerometers Monitored STS-93 Flight

Silicon Designs 1010J & 1210J Capacitive MEMS Accelerometers









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Why MEMS Are An Enabling Technology

- **You can simultaneously fabricate thousands of devices**
  - Micron-to-millimeter scale machines
  - Coordinated primitive functions by multiple devices can produce complex functions (like a computer!)
- **Integrated electronics can be co-manufactured**
  - Increased signal-to-noise ratios for sensors due to reduced parasitic loads
  - You can produce "smart" sensors and actuators for high reliability
- **Reduced size and power requirements for sensors**
- **Traditional off-chip components can be made on-chip**
  - High frequency inductors, bandpass filters, etc.

Possible MEMS Insertion Into Spacecraft Systems:

Command and Control Systems:

- -"MEMtronics" for ultra-radiation-hard and temperature-insensitive logic

Inertial Guidance Systems:

- - Microgyros and microaccelerometers
- - Micromirrors and microoptics for FOGs (fiber optic gyros)

Attitude Determination and Control Systems:

- - Micromachined sun and Earth sensors
- - Micromachined magnetometers

Propulsion Systems:

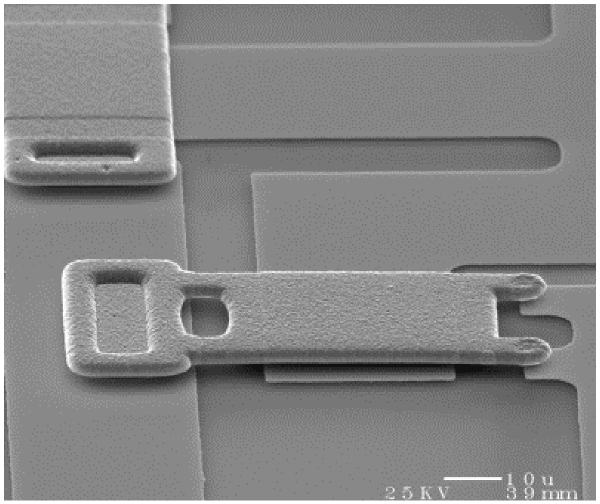
- - Micromachined pressure and chemical sensors
- - Arrays of single-shot thrusters ("digital propulsion")
- - Continuous or pulsed microthrusters

Communications and Radar Systems:

- - Very high bandwidth, low power, low resistance rf switches
- - Micromirrors and microoptics for laser communications

From "*Microengineering Space Systems*," by H. Helvajian and S.W. Janson, in Microengineering for Aerospace Systems edited by H.Helvajian, AIAA and The Aerospace Press, 1999

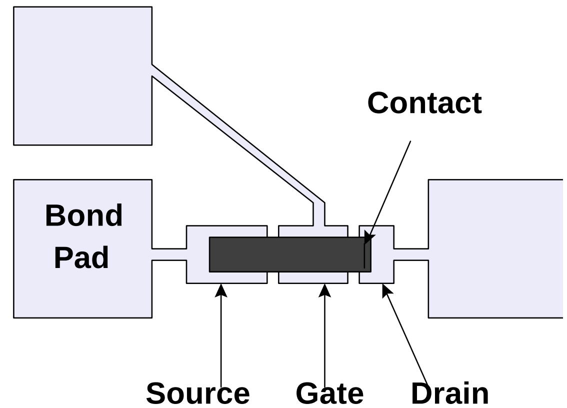
MEMS Switches: RF, Digital, or Analog

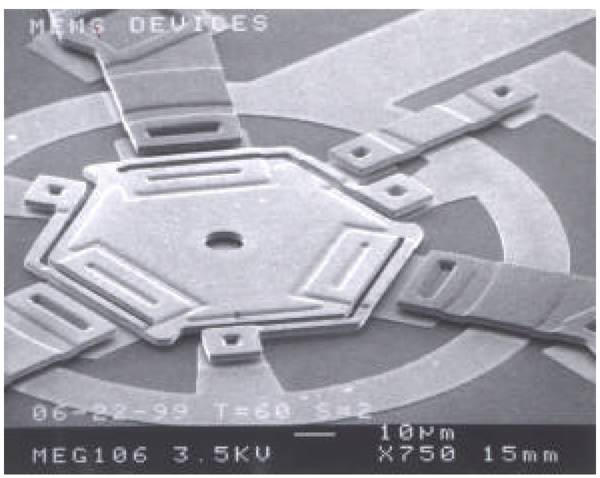


From:
P.M. Zavracky et al., “Micromechanical Switches Fabricated Using Nickel Surface Micromachining,” *J. Microelectromechanical Systems*, **6** #1, March 1997

http://www.ece.neu.edu/edsnu/zavracky/mfl/programs/relay/relay.html

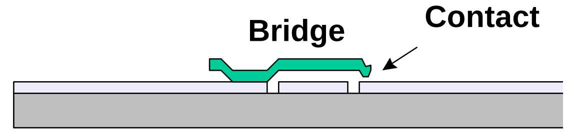
Top View:





From:
Aerospace Corp.

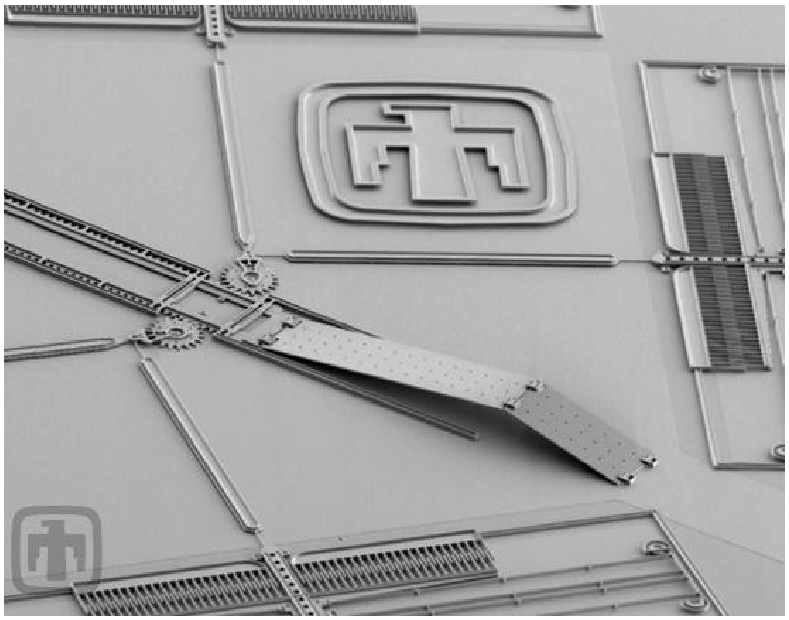
Side View:



- ***Super radiation-hard,***
- ***Wide operating temperature range***
- ***Low insertion loss***
- ***Wide bandwidth***

Optical MEMS Devices for Possible Space Applications

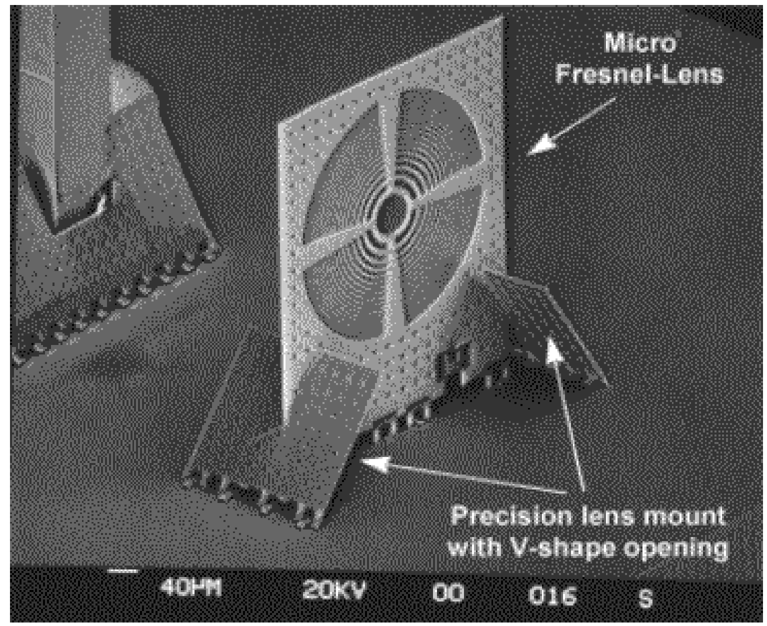
MEMS "Pop Up" Mirror (Sandia)



http://www.mdl.sandia.gov/micromachine/images6.html

See also: "Optics & MEMS" by S.J. Walker and D.J. Nagel, http://code6330.nrl.navy.mil/6336/moems.htm

MEMS "Pop Up" Lens (UCLA)

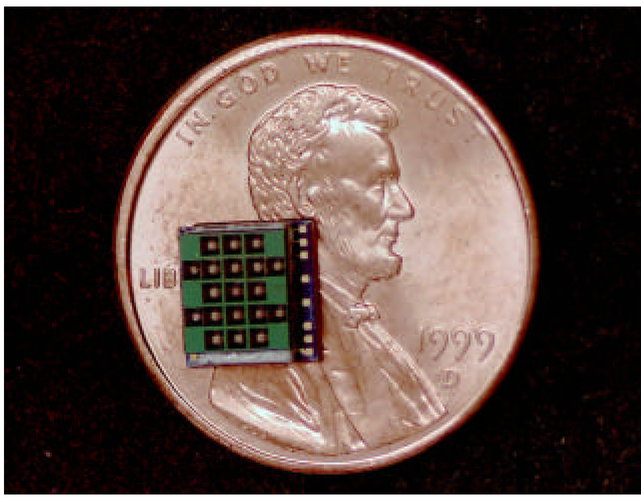


M.C. Wu, "Micromachining for Optical and Optoelectronic Systems," Proc. IEEE, Vol. 85, #11, Nov 1997; http://www.ee.ucla.edu/labs/laser/research/mot/1integrated.html

MEMS Thrusters and Components

MTO MEMS

15-Thruster "Chip" on STS-93



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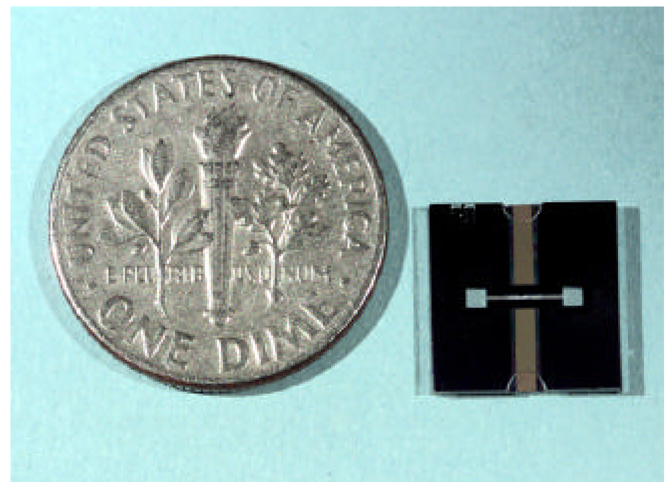
http://www.design.caltech.edu/
micropropulsion/index.html

***TRW, CalTech, and The Aerospace Corp*.**

Micro Isolation Valve



J. Mueller, S. Vago, D. Bame, D. Fitzgerald, and W. Tang," Proof-of-Concept Demonstration of a Micro-Isolation Valve," AIAA paper 99-2726, June 1999

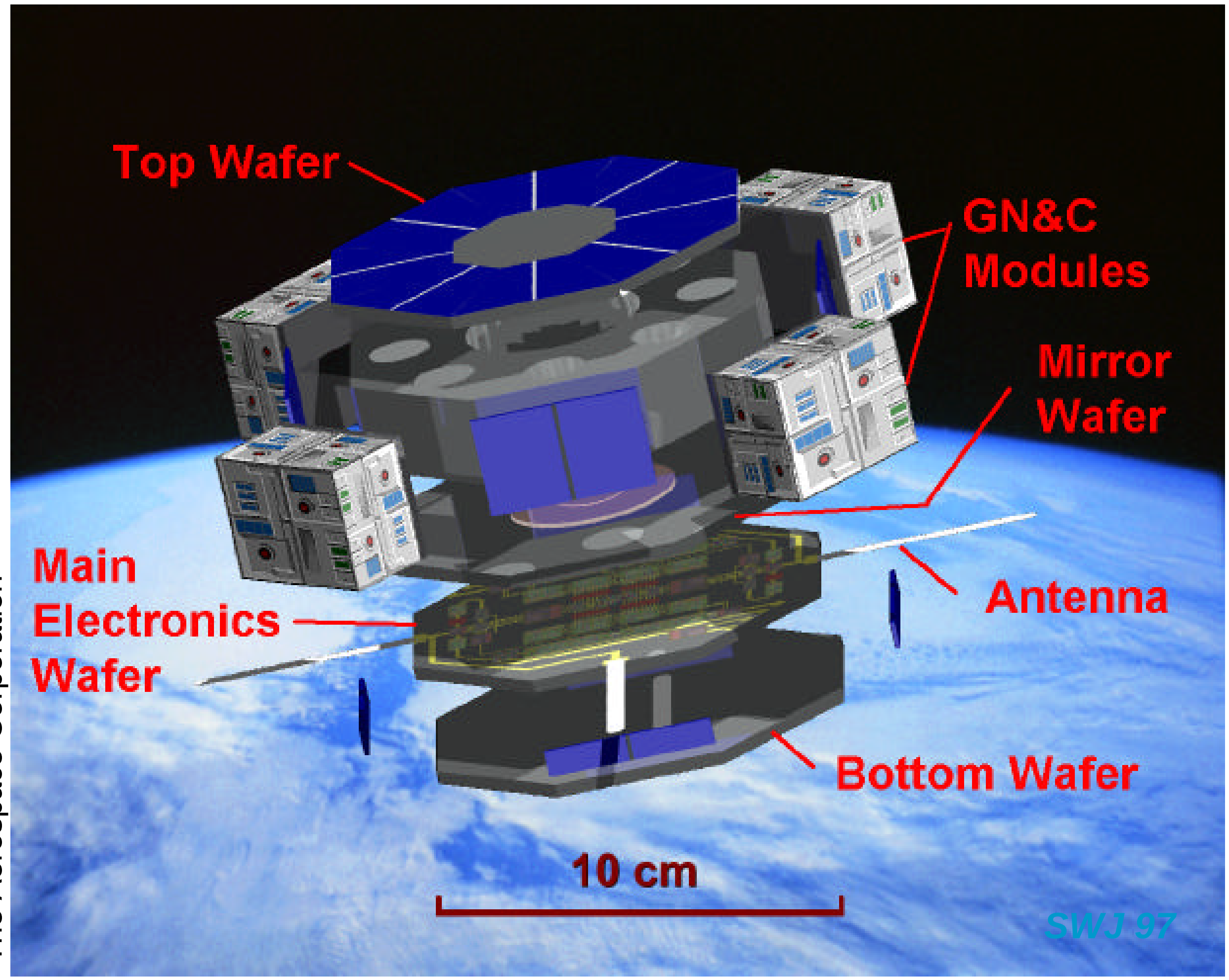
21st Century Micro/Nano/Picosatellites

- **Highly-integrated designs**
  - More functional elements, fewer piece-parts
  - Integrated diagnostics, self-test, and reconfiguration
  - “Silicon satellites”; grams-to-kilograms in mass
- **Batch or assembly-line fabrication in large lots (>100)**
  - Virtual satellites, e.g., km-scale sparse aperture arrays
  - Disposable satellites, e.g., satellite inspectors
  - Dense constellations for continuous Earth coverage
- **“Two-dimensional” satellites**
  - Large aperture/weight ratios, e.g., TechSat-21

A Silicon Nanosatellite Concept

Silicon serves as:

Structure,
Radiation shield,
Thermal control,
Optical material,
MEMS substrate,
Electronic substrate



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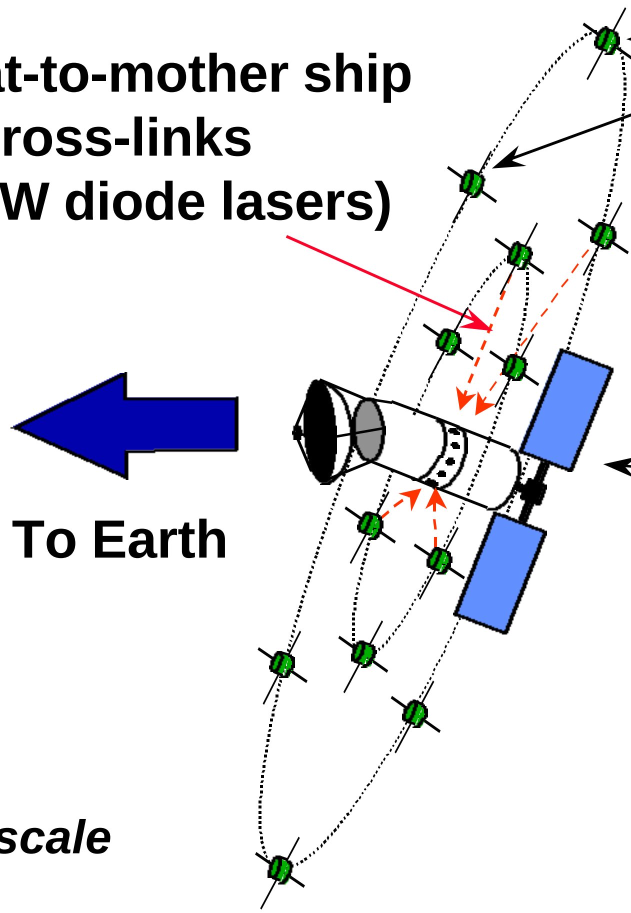
Nanosatellite Sparse Array Antenna Concept

Nanosat-to-mother ship cross-links (~10 mW diode lasers)



To Earth

Not to scale

Nanosats

N (order-of-100) nanosatellites with crossed-dipole antennas and low-power, optical cross-links. Nanosats co-orbit the mother ship and form a large sparse aperture receive antenna with multi-km effective diameter.

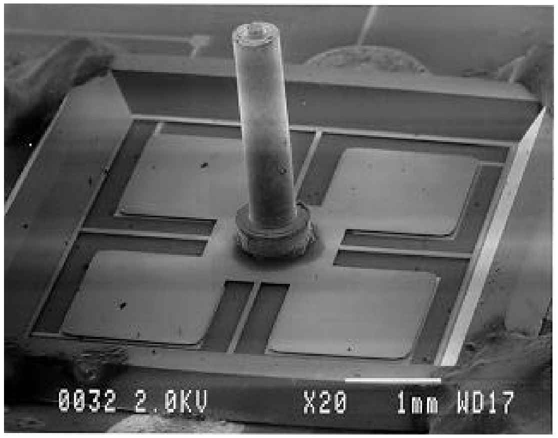
“Mother Ship”

Conventional spacecraft with N cross-link receivers, on-board coherent signal combining system, and nanosat position determination system. The high-gain antenna on the left is for direct communications with Earth (command and control, spot beam data, etc..).

Relevant R&D Activity (U.S.)

- **MEMS for space applications**
  - AFRL, AFOSR, DARPA
  - Sandia National Laboratories
  - NASA-JPL, NASA-Glenn
  - TRW, Draper Laboratories, Honeywell, Marotta Scientific, Hughes, Rockwell Science Center,…
  - CalTech, MIT, U.C. Berkeley, UCLA, …

NASA-JPL Microgyro



http://csmt.jpl.nasa.gov/mgyro.html

- **Integrated Micro/Nanospacecraft**
  - AFRL (TechSat-21)
  - NASA-JPL (X-2000 Deep Space Systems Technology Program)
  - Sandia (Nanosatellite)
  - NASA-Goddard (Nanosatellites for magnetospheric mapping)

Summary:

- MEMS and microtechnology can enable small, lightweight, but sophisticated spacecraft for challenging missions

- Mass-produced, integrated spacecraft can enable new space missions such as km-scale virtual spacecraft

- Spacecraft design and space architectures may radically change during the next decade